

Photometry of 40 LMC Cepheids

N. R. Tanvir^{1,2} and A. Boyle³

¹*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK.*

²*Department of Physical Sciences, University of Hertfordshire, College Lane, Hatfield, Herts. AL10 9AB, UK.*

³*Department of Physics, National University of Ireland, Galway, Ireland.*

Accepted . Received ; in original form

ABSTRACT

We present V and I_c CCD photometry for 40 LMC Cepheids at 1 to 3 epochs. This represents a significant increase in the number of LMC Cepheids with I -band data, and, as we show, is a useful addition to the sample which can be used to calibrate the period–luminosity relations in these important bands.

Key words: Cepheids, Large Magellanic Cloud

1 Jul 1999
1 INTRODUCTION

The bulk of recent extra-galactic Cepheid studies have used V -band observations to search for variability and characterise the light curves, and I -band observations to give colours and hence allow a correction for reddening (*e.g.* Tanvir *et al.* 1995). Usually this involves calculating apparent distance moduli in both bands and calculating the true modulus $\mu_o = \mu_{AV} - R_{VI}(\mu_{AV} - \mu_{AI})$. As emphasized by Tanvir (1997; hereafter T97), this approach is equivalent to determining reddening corrected Wesenheit indices for the Cepheids (see also Madore 1982; van den Bergh 1968), defined as

$$W_{VI} = \langle V \rangle - R_{VI}[\langle V \rangle - \langle I \rangle]$$

with $R_{VI} = A_V/E_{V-I}$, and fitting a suitable PL relation to them. However, the limited amount of photoelectric I -band data for Cepheids in the LMC is an impediment to calibrating this PL relation.

Fortunately reasonably good Wesenheit indices can be determined from observations at relatively few epochs. This is because the natural variations in colour and luminosity around a pulsation cycle mimic the effects of dust *i.e.* at their brightest the Cepheids are also at their bluest (see Madore 1985 for discussion in context of the “Feinheit” method). We illustrate this in figure 1 where we have taken the densely-sampled, high-quality data from Moffett *et al.* (1998) for several high-amplitude Cepheids, and resampled it many (10000) times at two randomly chosen epochs to see how the calculated value of W compares with that found from the full data-sets. The rms dispersion of the estimates around the true value is only 0.13 mags.

Here we report CCD observations of a large number (40) of LMC Cepheids, whose periods are already known from photographic work, at 1 to 3 epochs over 6 nights. The data presented will be combined with other data from

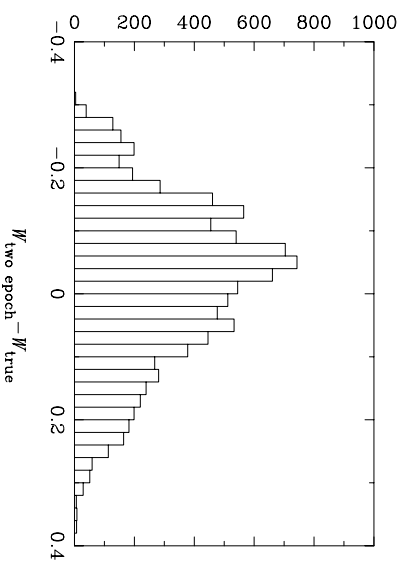


Figure 1. Histogram showing the error made in determining a Cepheid’s Wesenheit index from observations at two, randomly chosen epochs. This is based on resampling many times the dense, high-quality data for LMC Cepheids from Moffett *et al.* (1998). These Cepheids have periods in the region of 30 days and so are large amplitude and hence worst case. The formal rms dispersion is only 0.13 magnitudes, but note that there is a small offset in the mean of -0.016 mags which is a consequence of following the traditional approach of calculating magnitudes at mean intensity.

the literature in a future publication to determine new PL relations (Tanvir, in prep.).

2 OBSERVATIONS AND ANALYSIS

Our observations were obtained on the nights of the 14th to 19th of November 1996 with the Danish 1.5 m telescope at La Silla. The DFOSC camera was equipped with a 2048×2048 pixel, thinned Loral CCD (W11-4), which with 0.39 arcsec pixels gave a 13.3 arcmin field of view. Unfortunately

this chip was cosmetically poor around the edges and so we restricted the analysis to a circular region around the centre of radius 800 pixels.

The 28 primary targets were chosen to be Cepheids with periods between 8 and 50 days, the range explored in most HST extragalactic studies, which have little or no previous photoelectric *I*-band photometry, but often some *V*-band photometry. Finding charts from Hodge & Wright (1967) were used to locate the variables on the frames. The remainder of the sample consists of other Cepheids, usually of shorter period, which happened to lie in the same fields and which typically have no other photoelectric photometry.

V- and *I*-band exposures were obtained at each epoch, with exposure times ranging from 10 s to 60 s. Every night was photometric, and we obtained flat-fields and multiple standard star observations (specifically fields in SA95, SA98, SA114 and around T Phe from Landolt 1992) so that each night could be calibrated independently onto the *VI*_c systems. In practice the zero-points of the magnitude scales agreed from night to night to 0.01 mag. Colour terms were determined by combining all the standard star photometry and, for the difference in the average colour between the standards and the Cepheids, amounted to less than 0.01 mags in each case. Although the seeing varied, sometimes quite rapidly, between about 0.9 arcsec and about 1.7 arcsec, we found that magnitudes measured in a 6 arcsec diameter aperture, over this range, were not very sensitive to the seeing.

Nightly extinction coefficients were taken from the data-base of the Geneva Observatory Photometric group (<http://obswww.unige.ch/photom/extlast.html>; see Burki *et al.* 1995), and range between 0.12 and 0.14 mag per air-mass for the *V*-band, in excellent agreement with our standard star observations. Although *I*-band extinction coefficients were not available for the nights of our run, we adopted a value of 0.06 mag per airmass based on the typical values for other nights which were tabulated. Air-masses for the observations were typically in the range 1.3 to 1.6, which is inevitable given the declination of the LMC, while the standard fields, although observed at a wide range of air-masses, were in most cases lower at 1.1 to 1.2.

Each frame was debiased and flat-fielded in the normal way. Interactive aperture photometry was performed with the *apphot.phot* routine within IRAF, for the target Cepheids, standard stars and also for several field stars in each frame. Each star was measured in apertures of 2, 4, 8, 16 and 32 pixels radius. In most cases, the 4 pixel radius aperture was used, to minimize any small crowding errors, and an aperture correction to 16 pixels was determined from a number of stars in the frame and other frames of similar seeing taken on the same night. The sky level was determined from the pixels in a large annulus around the program star.

3 RESULTS

The photometry is listed in table 1. For each variable the period is given in parentheses and the three columns are (1) the modified Julian date of observations, (2) *V* and (3) *I*_c. Since each night was calibrated independently, it is possible to get fairly good estimates of the true photometric errors by comparing the magnitudes of non-variable stars observed

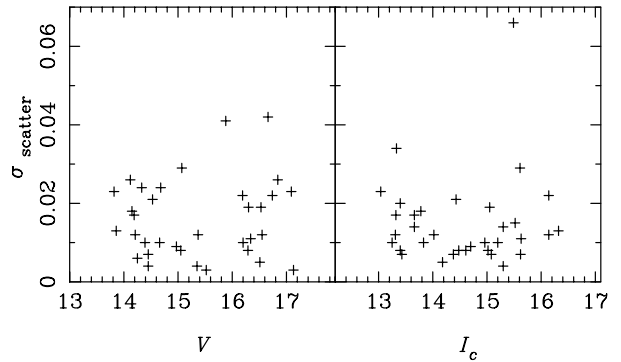


Figure 2. Estimates of the photometric error from the scatter in the magnitudes of (assumed) non-variable stars observed on three occasions. Since each night is calibrated independently, this gives an indication of the true photometric errors. Although there may be a small increase in σ_{scatter} at faint magnitudes, at bright magnitudes it is certainly dominated by the calibration uncertainties and the limiting value is around 0.015 mags in each case.

on different nights. In figure 2 this is done for a set of stars which were observed on 3 occasions, and shows that typical errors in the magnitude range of interest are around 0.015 magnitudes. Although small, this is greater than the formal errors reported by phot, showing that, as expected, the calibration and aperture corrections are also important sources of uncertainty. This also explains why the dispersion increases very little with magnitude. As another test of our photometry, we also observed the two LMC photometric standard stars CPD66349 and CPD66350 (Menzies *et al.* 1989). First transforming the standard magnitudes to Landolt's (1983) system via the equations given in Menzies *et al.* (1991) we obtain the following differences in the sense of *us minus standard* for the two stars: -0.022 and -0.003 in *V* and -0.017 and -0.017 in *I*_c. Again this is reasonably consistent with a typical error of 0.015 mags.

4 DISCUSSION

As we have said, the primary motivation for obtaining this data is to combine it with other data from the literature to provide a large sample of Cepheids with which to explore the calibration of the Cepheid period-luminosity relations in the LMC (Tanvir in prep.). Here we simply plot the intensity mean magnitudes in each band and Wesenheit indices (figure 3) where we have taken $R_{VI} = 2.45$ (T97). This demonstrates that, even with a small number of epochs, the Wesenheit indices indeed produce an impressively tight PL relation.

ACKNOWLEDGMENTS

AB acknowledges an RGO summer studentship.

REFERENCES

Burki, G. *et al.*, 1995, ESO Messenger, 80, 34.

Table 1. V and I_c photometry for our sample. The periods in days, given in parentheses, are either taken from Payne-Gaposchkin (1971), or are re-determined by us for those cases where other photoelectric V -band photometry exists in the literature.

<i>HV873</i> (34.427)			<i>HV875</i> (30.328)			<i>HV878</i> (23.304)		
50402.32	13.406	12.256	50402.32	13.286	12.326	50402.32	13.508	12.570
50407.06	13.636	12.524	50407.07	13.100	12.268	50402.33	13.507	12.546
						50407.07	13.845	12.798
<i>HV881</i> (35.743)			<i>HV882</i> (31.795)			<i>HV886</i> (23.98)		
50402.33	12.561	11.900	50402.33	12.793	12.092	50403.33	13.755	12.771
50407.07	12.754	11.932	50407.08	13.008	12.167	50407.08	13.193	12.496
<i>HV889</i> (25.805)			<i>HV900</i> (47.51)			<i>HV902</i> (26.346)		
50403.33	14.051	12.906	50403.34	13.026	11.912	50402.36	12.796	12.125
50407.09	14.038	12.986				50407.09	13.065	12.213
<i>HV909</i> (37.565)			<i>HV955</i> (13.737)			<i>HV1003</i> (24.345)		
50402.36	12.865	11.881	50402.35	13.526	12.926	50403.35	13.550	12.561
50407.10	12.974	11.995	50406.22	14.035	13.162	50407.12	13.549	12.631
			50407.11	14.120	13.208			
<i>HV1005</i> (18.711)			<i>HV2251</i> (27.916)			<i>HV2254</i> (3.168)		
50403.35	13.702	12.971	50403.33	13.539	12.454	50403.33	16.198	15.459
50407.13	13.991	13.006	50407.08	13.639	12.610	50407.08	15.370	14.924
<i>HV2257</i> (39.37)			<i>HV2291</i> (22.328)			<i>HV2295</i> (7.846)		
50402.32	13.113	11.982	50403.33	14.335	13.301	50403.33	14.855	14.038
50402.33	13.123	11.995	50407.09	13.640	12.791	50407.09	15.201	14.292
50407.07	13.255	12.122						
<i>HV2432</i> (10.925)			<i>HV2523</i> (6.784)			<i>HV2527</i> (12.949)		
50402.34	14.585	13.690	50402.35	15.089	14.207	50402.35	14.209	13.50
50404.37	14.329	13.607	50405.36	14.825	14.061	50405.36	14.379	13.52
			50407.11	14.987	14.148	50407.11	14.550	13.579
<i>HV2549</i> (16.216)			<i>HV2579</i> (13.425)			<i>HV2662</i> (12.075)		
50402.36	14.097	13.191	50406.23	14.456	13.490	50403.34	14.546	13.533
50407.11	13.146	12.624	50407.12	14.314	13.430	50405.37	14.631	13.655
						50407.12	14.406	13.544
<i>HV2722</i> (8.027)			<i>HV2738</i> (8.337)			<i>HV5511</i> (3.340)		
50403.36	14.941	14.134	50403.36	14.418	13.760	50402.32	16.299	15.431
50404.36	14.561	13.911	50404.36	14.496	13.759	50407.06	15.742	15.096
50407.13	14.386	13.742	50407.13	14.924	14.023			
<i>HV6105</i> (10.440)			<i>HV8036</i> (28.38)			<i>HV12248</i> (10.912)		
50402.34	15.104	14.183	50402.30	13.863	12.705	50403.36	14.763	13.800
50404.36	14.617	13.892	50407.04	14.001	12.864	50406.23	14.475	13.692
50407.10	14.844	13.937				50407.14	14.361	13.620
<i>HV12253</i> (12.574)			<i>HV12416</i> (3.928)			<i>HV12426</i> (2.550)		
50404.35	14.790	13.857	50402.32	15.994	15.088	50402.33	15.795	15.264
50406.24	14.644	13.771	50407.06	16.087	15.245	50407.07	15.515	15.150
50407.14	13.779	13.256						
<i>HV12471</i> (15.851)			<i>HV12503</i> (2.731)			<i>HV12619</i> (3.481) ^a		
50402.31	14.857	13.757	50402.32	15.861	15.277	50403.34	15.295	14.578
50405.36	14.309	13.429	50407.07	16.260	15.581	50405.37	15.215	14.535
50407.05	14.432	13.448				50407.12	15.230	14.576
<i>HV12716</i> (11.248)			<i>HV12787</i> (3.676)			<i>U1</i> (22.54)		
50402.30	14.391	13.535	50402.34	15.375	14.847	50402.31	14.594	13.325
50405.36	14.837	13.800	50404.36	15.955	15.170	50407.04	14.570	13.447
50407.03	15.020	13.960	50407.10	15.667	14.973			
<i>U11</i> (20.077)								
50402.31	14.337	13.201						
50407.05	14.249	13.275						

^a Note that there is some uncertainty about the period of HV12619, which is given by Payne-Gaposchkin (1971) as 2.480646, but whose position within her table 5 suggests a typographical error and that the leading number should be a 3. However, given that, in addition, this variable is flagged as having significant scatter, we recommend it be treated with caution.

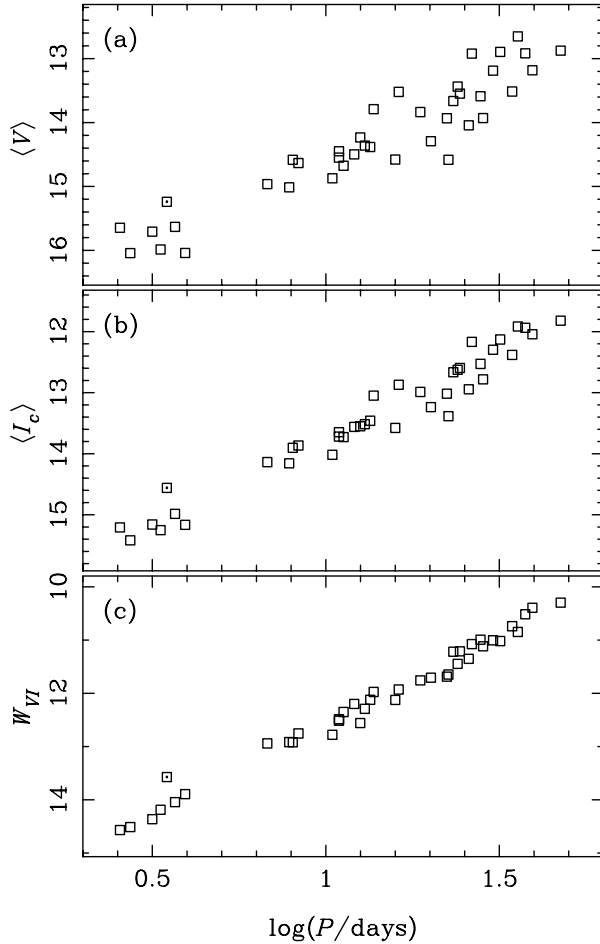


Figure 3. Intensity mean magnitudes in (a) V and (b) I_c , and (c) Wesenheit indices for our sample plotted against log period. We have not corrected here for the small bias in the intensity means caused by the undersampling, which was pointed out in the caption to figure 1. Note that the scatter is large in V and I_c , but much smaller in W_{VI} as expected. The most extreme outlier, indicated by a central dot, is in fact HV12619 which, as noted in the caption to table 1, is of uncertain status and period.

- Hodge, P.W. & Wright, F.W., 1967, *The Large Magellanic Cloud*, Smithsonian press (Washington).
 Landolt, A.U., 1983, *AJ*, 88, 439.
 Landolt, A.U., 1992, *AJ*, 104, 340.
 Madore, B.F., 1982, *ApJ*, 253, 575.
 Madore, B.F., 1985, *ApJ*, 298, 340.
 Menzies, J.W., Cousins, A.W.J., Banfield, R.M. & Laing, J.D., 1989, *SAAO Circ.*, 13, 1.
 Menzies, J.W. *et al.*, 1991, *MNRAS*, 248, 642.
 Moffett, T.J., Gieren, W.P., Barnes, T.G. & Gomez, M., 1998, *ApJS*, 117, 135.
 Payne-Gaposchkin, C.H., 1971, *Smithsonian Contributions to Astrophysics*, 13, 1.
 Tanvir, N.R., Shanks, T., Ferguson, H.C. & Robinson, D.R.T., 1995, *Nature*, 377, 27.
 Tanvir, N.R., 1997, *The Extragalactic Distance Scale*, eds. Livio *et al.*, CUP, p 91.
 van den Bergh, S., 1968, *JRASC*, 62, 145.